REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE (DD-MM-YYYY) 01-07-2003	2. REPORT TYPE technical	3. DATES COVERED (From - To) 10/18/2001 - 10/17/2002

4. TITLE AND SUBTITLE
Analysis of steep and breaking ocean surface waves using data from an airborne scanning lidar system

5a. CONTRACT NUMBER
N00173-02-1-G902

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Tetsu Hara

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Graduate School of Oceanography
University of Rhode Island
Narragansett, RI 02882

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
NRL
Stennis Space Center, MS 39529-5004

10. SPONSOR/MONITOR'S ACRONYM(S)
NRL

11. SPONSORING/MONITORING AGENCY REPORT NUMBER

12. DISTRIBUTION AVAILABILITY STATEMENT
Unclassified

13. SUPPLEMENTARY NOTES

14. ABSTRACT
See attached.

20030812 128

15. SUBJECT TERMS
breaking waves, scanning lidar system, ocean surface waves

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Tetsu Hara
a. REPORT U	b. ABSTRACT U	c. THIS PAGE U		5	19b. TELEPONE NUMBER (Include area code) 401-874-6509

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI-Std Z39-18

Abstract

It is clear intuitively that at high wind speeds breaking waves become increasingly important to air-sea interaction. Recently, an airborne scanning lidar system was used to obtain 2D spatial topography of ocean surface waves. Such data were used to study the wavenumber spectrum in detail. Here, we applied the wavelet transform to the 1D surface topography in the direction of mean wind. We then estimated the steep wave statistics, $\Lambda_T(k)$, and compared the results with other field observations. We have shown that the wavelet analysis methodology is able to track steep wave events and give estimates of the amount of high wave slope events that cover a given area of ocean. Analysis of the results shows that high wave slope crests appear over the entire range of wavenumbers resolved, with a large amount being much shorter in wavelength than the dominant wave. At low wave slope thresholds, the total crest length is approximately independent of wind forcing for all wave fields considered. All wave fields studied have the same amount of wave crests regardless of wind forcing at low slope threshold. If the steep wave statistic is hypothesized to evolve into the breaking wave statistic at a specific wave slope threshold, comparison of $\Lambda_T(k)$ with previous independent measurements of the breaking wave statistic gives a wave slope threshold of 0.12. In addition, comparison of the steep wave statistic at this extrapolated wave slope threshold with independent breaking wave measurements suggest that other factors besides the wind speed control the level of the steep wave statistic.

Analysis of steep and breaking ocean surface waves using data from an airborne scanning lidar system

Technical Report

Grant Number: N00173-02-1-G902

Duration: 18 October 2001 – 17 October 2002

Tetsu Hara
Graduate School of Oceanography, University of Rhode Island, Narragansett, RI 02882
Telephone: 401-874-6509; E-mail: thara@uri.edu

Project Description

It is clear intuitively that at high wind speeds breaking waves become increasingly important to air-sea interaction. However, the role of these breaking waves on air-sea fluxes is at present almost completely unknown, partly because it is difficult to define and quantify surface breaking waves from field observations.

There have been attempts to quantify breaking waves using high-resolution radar (Phillips et al., 2001) and using visual observations of whitecap statistics (Melville and Matusov, 2002). In these studies, radar or visual observations are used to determine the function $\Lambda(\vec{c})$, which is defined as the average length of breaking front per unit surface area per unit speed interval of breaking front propagation. Although these studies propose promising approaches of quantifying breaking waves, it is desirable to develop an independent approach to quantify steep and breaking waves using direct observations of surface wave topography.

Recently, an airborne scanning lidar system has been used to obtain 2D spatial topography of ocean surface waves. Such data have been used to study the wavenumber spectrum in detail (Hwang et al., 2000a, 2000b). These studies, however, are based on Fourier analyses of surface topography and therefore do not yield any information about steep and breaking wave events. In this project, we propose to develop a new algorithm to identify and quantify steep and breaking waves using the same wave topography images.

Recent laboratory observations (private communication with Dr. Guillemette Caulliez, IRPHE - Laboratoire IOA) indicate that the shape of breaking waves is self-similar and is best characterized by the maximum slope exceeding a critical threshold, regardless of wave scales. If this result is also valid under field conditions, it is feasible to identify breaking waves from the 2D topographic images by searching locations where local surface slope exceeds a critical threshold. Although the propagation speed of breaking wave crests cannot be determined directly from the 2D images, it is possible to determine the spatial scale (wavenumber) of the waves that are breaking and then convert the spatial scale to the propagation speed using the dispersion relationship.

Technical Approach

Specifically, the following approaches were taken:

- We applied the wavelet transform to the 1D surface topography in the direction of mean wind. The result of the wavelet spectrum was rescaled such that the local maximum of the spectrum corresponds to the local slope of surface waves.

- We used a critical value of the wavelet spectrum as a threshold to determine steep and breaking waves.

- We counted the number of steep wave events and determined the associated scale (wavenumber) of each event.

- We convert the results in the form of $\Lambda_T(k)$, the steep wave statistics, and compared the results with other field observations.

- We also applied these procedures to successive parallel 1D surface topography lines and determine the crest length of each breaking wave event.

These tasks were completed mainly by a graduate student at the Graduate School of Oceanography, University of Rhode Island, under the supervision of the PI.

Results

Since the results are reported in detail in Scott (2003) and also in Scott et al. (2003a, 2003b), only a brief summary is presented here.

- The wavelet analysis methodology is able to track steep wave events and give estimates of the amount of high wave slope events that cover a given area of ocean. Analysis of the results shows that high wave slope crests appear over the entire range of wavenumbers resolved, with a large amount being much shorter in wavelength than the dominant wave. This is qualitatively consistent with results of Ding and Farmer (1994). At low wave slope thresholds, the total crest length is approximately independent of wind forcing for all wave fields considered. All wave fields studied have the same amount of wave crests regardless of wind forcing at low slope threshold.

- If the steep wave statistic is hypothesized to evolve into the breaking wave statistic at a specific wave slope threshold, comparison of $\Lambda_T(k)$ with previous independent measurements of the breaking wave statistic gives a wave slope threshold of 0.12. This is much lower than the traditional Stokian value of 0.4. This threshold is also consistent with the results of the numerical studies of Dold and Peregrine (1986). In addition, comparison of the steep wave statistic at this extrapolated wave slope threshold with independent breaking wave measurements suggest that other factors besides the wind speed control the level of the steep wave statistic.

- Comparison of $\Lambda_T(k)$ to the saturation spectrum $B(k)$ demonstrates their proportionality at the high wave slope thresholds. However the relationship of the saturation spectrum to the steep wave statistic is not unique.

- Comparison of the integrated two-dimensional lambda function $\Lambda_{\cdot T}(k)$ to the one-dimensional lambda function obtained by one-dimensional analysis, $\Lambda_T(k)$ shows consistency to first order.

- The crest directionality statistic shows that most of the steep wave crests are normal to the direction of the wind even at low wave slope thresholds. This is not consistent with the wavenumber spectrum that shows a broad directional spreading at high wavenumbers. The lack of consistency is attributed to the different premises assumed in the different signal processing methodologies used. The crest length statistics demonstrate that the wave field is dominated by small crest length/wavelength ratios.

- Sensitivity studies show that the difference in the use of integer scales, binned integer scales, and logarithmic scales is negligible. Thus the resulting trends are most likely indicative of the true statistical characteristics of the wave fields.

References:

Ding, L., and D. Farmer (1994). Observations of breaking surface wave statistics. *Journal of Physical Oceanography*, **24**, 1368 –1387.

Dold , J. W., and D. H. Peregrine (1986). Water-wave modulation. *Proceedings of the 20th International Conference in Coastal Engineering*, Taipei, Taiwan, ASCE, 163-175.

Hwang, P., D. Wang, E. Walsh, W. Krabill, and R. Swift (2000a). Airborne measurements of the wavenumber spectra of ocean surface waves. part I: spectral slope and dimensionless spectral coefficient. *Journal of Physical Oceanography*, **30**, 2753-2767.

Hwang, P., D. Wang, E. Walsh, W. Krabill, and R. Swift (2000b). Airborne measurements of the wavenumber spectra of ocean surface waves. part II: directional distribution. *Journal of Physical Oceanography*, **30**, 2768-2787.

Melville, W. K., and P. Matusov (2002). Distribution of breaking waves at the ocean surface waves. *Nature*, **417**, 58-63.

Phillips, O. M., F. L. Posner, and J. P. Hansen (2001). High range resolution radar measurements of the speed distribution of breaking events in wind-generated ocean waves: surface impulse and wave energy dissipation rates. *Journal of Physical Oceanography*, **31**, 450-460.

Publications:

Scott, N. (2003). Observations of the wind-wave spectrum and steep wave statistics in open ocean waters. Ph.D. Thesis, University of Rhode Island.

Scott, N, T. Hara, P. Hwang, E.J. Walsh (2003a). Observations of Steep Wave Statistics in Open Ocean Waters. *Journal of Atmospheric and Oceanic Techonology*, in preparation.

Scott, N, T. Hara, P. Hwang, E.J. Walsh (2003b). Estimating Directionality and Crest Length Statistics of Steep Waves in Open Ocean Waters. *Journal of Atmospheric and Oceanic Techonology*, in preparation.